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Virtual Seismometers in Geothermal Systems : Using Microquakes to Illuminate the Subsurface

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ABSTRACT

A natural response to fluid injection at enhanced geothermal sites is the creation of microseismicity. Thousands of microquakes are often associated with an injection well. When processed using novel geophysical techniques, these microquakes effectively illuminate the subsurface, and can be used to monitor plume growth and identify otherwise hidden structures. The virtual seismometer method (VSM) is a new technique of seismic interferometry that provides precise estimates of the GF between earthquakes. It is very sensitive to the source parameters (location, mechanism and magnitude) and to the Earth structure in the source region.

Using VSM, we are able to focus sharply on the cloud of microseismicity. We can monitor the evolution of seismicity over time, measure changes in the style of faulting and sort microseisms by location and magnitude. Our ultimate intent is to use it to image structures within the microseismic cloud in an attempt to identify previously un-observed fault zones. In simple terms VSM involves correlating the waveforms from a pair of events recorded at an individual station and then stacking the results over all stations to obtain the final result. In the far-field, when most of the stations in a network fall along a line between the two events, the result is an estimate of the GF between the two, modified by the source terms. In this geometry each earthquake is effectively a virtual seismometer recording all the others. When applied to microquakes, this alignment is often not met, and we need to address the effects of the geometry between the two microquakes relative to each seismometer. Nonetheless, the technique is quite robust, and highly sensitive to the microseismic cloud.

1. INTRODUCTION

In seismology, the Green's function (GF) is defined as the response of the Earth at one point due to an impulsive source at another. In simple terms, GFs are the data recorded by seismometers once the peculiarities of the source and instrument are removed. Because of reciprocity, the seismic record would be the same even if the locations of the impulsive source and the seismometer were switched. In recent years, seismologists have used this principle in the emerging field of seismic interferometry to treat seismometers as virtual earthquakes and earthquakes as virtual seismometers.

In 2003, using a fundamentally new technique for studying Earth structure, Campillo and Paul used the cross correlation of the scattered energy that arrives after an earthquake (called the coda) recorded at different seismic stations to obtain the GF of the Earth between the stations (Campillo and Paul, 2003). Since then, the field of seismic interferometry has rapidly expanded and produced highly detailed images of the crust and upper mantle. To date, seismic interferometry has focused on using the ambient noise field to obtain image the interior of the Earth between pairs of stations. However, it is straightforward to flip the geometry used by Campillo and Paul and focus instead on the structure between pairs of earthquakes. Hong and Menke (2006) took advantage of this theory to study wear along the San Jacinto fault. The theory was developed more completely by Curtis et al. (2009), who demonstrated that you can convert earthquakes into "virtual seismometers" by using the correlation properties of records from distant arrays.

Our method, similar to that of Curtis et al., involves correlating the coda of pairs of earthquakes recorded at individual seismic stations and then stacking the results over all stations to obtain the final GF. In a proof of concept experiment, we demonstrated that we can accurately recover the signal expected for waves propagating between 40 earthquakes originating along the Blanco Fracture Zone, a 350 km long active transform fault separating the Juan de Fuca and Pacific Plates. We were able to measure the GFs for hundreds of paths. These match closely with those predicted by large-scale 3D models and the differences illuminate fine details of the fault zone (figure 1).

By effectively replacing each earthquake with a "virtual seismometer" recording all the others, the technique isolates the portion of the data that is sensitive to the source region and dramatically increases our ability to see into tectonically active features where seismic stations either can't or haven't been located, such as at depth in fault zones.

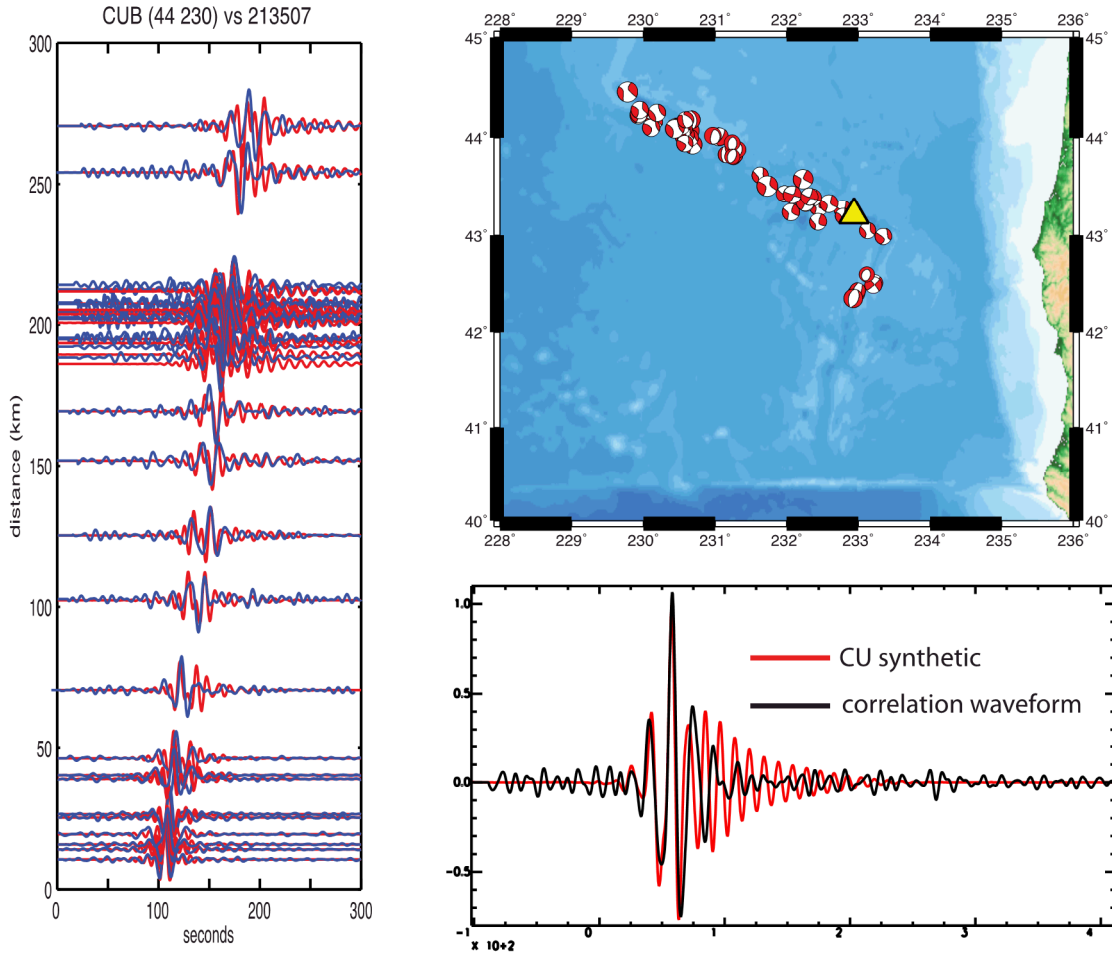


Figure 1: Proof of concept of the VSM applied to far-field data. Top right: earthquakes along the Blanco fault zone, one of which is treated as a virtual seismometer recording the others (yellow triangle on map). The correlation waveform GF (black) compared with the synthetic seismogram expected for that trace using the CU Boulder 3D Earth model. Left: the same for all the traces in the sequence relative to the reference “virtual seismometer”.

In many ways VSM is the converse of ambient noise correlation (ANC), also known as the “virtual earthquake” technique. Each technique has its strengths relative to the other. VSM is very fast, only a few minutes of data are needed, compared to the weeks to years of continuous data often required for ANC. Furthermore, the GF obtained by VSM has the same frequency content as the earthquakes, while the spectrum of ANC is determined by the natural background noise. For microseismic studies, this allows us to obtain very high frequency estimates of the GF between microquakes. Both techniques gain power rapidly as more elements are added to the system according to the equation $N*(N-1)/2$. For ANC, these elements are the individual seismometers, for VSM the elements are the individual earthquakes. The key strength of ANC is that timing and location of the elements are perfectly known and the GF is equivalent to that of a simple impulsive source. For VSM, neither the timing nor the location of the elements is known and the correlation waveform is the GF, modified by both moment tensors. For this reason, ANC is quite sensitive to the heterogeneities in the Earth structure, while VSM is most sensitive to the source parameters, which need to be accounted for before Earth structure can be recovered.

2. MICROQUAKES AS VIRTUAL SEISMOMETERS

In the far-field, when most of the stations in a network fall along a line between two earthquakes, the result of the correlation is an estimate of the GF between the two, modified by the source terms. In this geometry each earthquake is effectively a virtual seismometer recording all the others. Even when two earthquakes line up at an angle to the recording network, the effects of the geometry can be removed before stacking to obtain the GF estimate. However, in microseismic systems, the uncertainty in location and origin time are compounded by the fact that the distance between individual stations in the recording network may be much farther from one another than they are from the zone of microseismicity and the effects of geometry become more pronounced.

In this study we develop the techniques to apply VSM to microseismic data and test those techniques on recorded data. Figure 2 illustrates the type of information we can obtain by even simple measurements on the correlations. These are synthetic test cases for microquake sources within the Newberry 3D model. One thousand randomly scattered instruments were placed at the surface of the model and the VSM technique was applied to the synthetic records. Note that even simple measurements on the raw correlations provide information. We can detect small differences in location between the sources by measuring differences in phase arrival times. The moment tensor of the source is also dramatically illuminated by measuring sign and the amplitude of the VSM waveforms.

Adjoint techniques (Tromp, Tape and Liu, 2005) allow us to calculate the sensitivity of the model parameters to the observables and show that kernels for virtual seismometers are very comparable to those for actual seismometers and for many geometries, even a simple stack of the correlation waveforms result in a match for the correct GF.

Finally, we apply VSM to microseisms recorded at the Newberry EGS site. We use precise relocations of the microseisms to constrain the degrees of freedom in the system and illustrate how the wavefield can be captured when many microseisms are used as virtual seismometers recording the rest.

Virtual seismometers are very sensitive to the relative locations and focal mechanisms of the sources

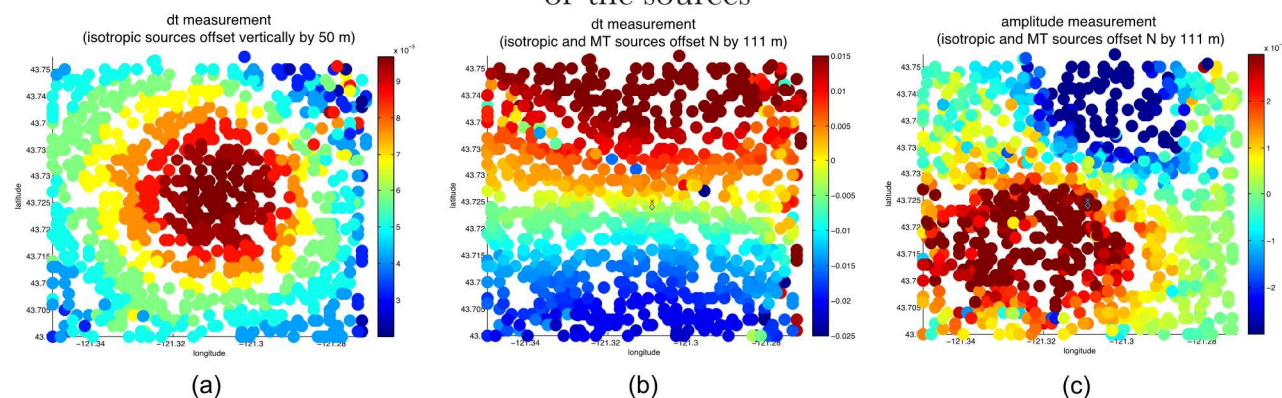


Figure 2: Synthetic test cases for sources at roughly 2 km depth in the Newberry 3D model. (a) Two sources offset vertically by 50 m create a distinctive bullseye pattern in the VSM arrival time measurement. (b) Two sources offset laterally create a simple linear pattern in the arrival time measurement. These represent the projection of an ellipse onto the surface. (c) Measurement of the amplitudes of the VSM records from the experiment shown in (b). Note that the sign of the amplitude measurement illuminates the focal mechanism.

3. CONCLUSIONS

Microseismicity is closely associated with geothermal development and can be used to monitor the evolution of the pressure field due to fluid injection. VSM is a technique that allows us to focus directly on this zone of microseismicity, illuminating the subsurface precisely where the pressures are changing. This has the potential to image the evolution of seismicity over time, including changes in the style of faulting as injection proceeds. Given sufficient microseismicity we can begin to calculate detailed evolution of the wavefield.

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